A wafer-level liquid cavity integrated amperometric gas sensor with ppb-level nitric oxide gas sensitivity

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Abstract

A miniaturized amperometric nitric oxide (NO) gas sensor based on wafer-level fabrication of electrodes and a liquid electrolyte chamber is reported in this paper. The sensor is able to detect NO gas concentrations of the order of parts per billion (ppb) levels and has a measured sensitivity of 0.04 nA ppb\(^{-1}\) with a response time of approximately 12 s. A sufficiently high selectivity of the sensor to interfering gases such as carbon monoxide (CO) and to ammonia (NH\(_3\)) makes it potentially relevant for monitoring of asthma. In addition, the sensor was characterized for electrolyte evaporation which indicated a sensor operation lifetime allowing approximately 200 measurements.

Keywords: nitric oxide, amperometric, gas sensor, MEMS, silicon, Nafion

1. Introduction

Amperometric gas sensors are, due to their versatility, applied in wide range of fields from health care to pollution monitoring [1]. In the health care sector, amperometric gas sensors are finding increased use in gas monitoring instruments [2]. For example, in an asthma measurement instrument that monitors the inflammation in the airways of the lungs, an amperometric gas sensor measures the concentration of nitric oxide (NO) in the exhaled breath [3]. In adults, a NO gas concentration above 50 ppb typically indicates the presence of an inflammation [4–6]. The asthma measuring instruments currently available in the market today are bench-top instruments that typically are used in healthcare settings. However, if the instrument could be made smaller, asthma patients could have their own personal portable monitor which could be beneficial in the management of the disease. The reason for the large size of the current instruments is that the commercially available parts-per-billion (ppb)-level NO gas sensors have a slow NO gas response time (40 to 60 s) which makes it necessary to incorporate buffering components to store and pump the gas at a low flow rate to the sensor [3]. In addition, commercially available NO sensors are typically manufactured by serial (sometimes manual) assembly of individual components which leads to relatively costly sensors that are a few cm\(^3\) large in size and which, consequently, responds slowly to the gas. Therefore, in order for the instrument to be hand-held and reduce cost there is a need for batch-fabricated, fast sensors, that responds in real time without the need of extra space-consuming buffering components.

Metal oxide gas sensors have a potential to be used in hand-held instruments due to their small size and compatibility with batch fabrication. However, the slow response time, cross sensitivity and high power consumption, are the drawbacks [7, 8] which make them unsuitable for asthma monitoring. Amperometric microsensors with Nafion\textsuperscript{TM} as a solid electrolyte, on the other hand, offer higher sensitivity, faster response and lower power consumption than metal oxide gas sensors [9, 10]. However, these solid electrolyte gas sensors are prone to be sensitive to humidity and are therefore not suitable for asthma monitoring. Currently, commercial amperometric gas sensors with liquid electrolyte, which are less sensitive to humidity variations, use multiple layers of Teflon\textsuperscript{™}-based membranes to protect the electrolyte from evaporation.
The main drawback of this method is an increased response time which inhibits real time gas concentration measurements. Other demonstrated approaches in measuring low concentrations of NO with integrated sensors include potentiometric sensing and indirect measurements of NO₂. Potentiometric sensors have not yet demonstrated relevant detection levels at the short response times needed for real-time measurements. Indirect measurements of NO₂ has shown promising results for breath samples, however the applicability for asthma monitoring using this indirect method of NO conversion and measurement of NO₂ still remain to be proven in large patient studies.

Recently, we developed a new NO sensor that combined the advantageous effects of Nafion with a liquid electrolyte reservoir to avoid large humidity dependency. This sensor had a fast response and a high sensitivity, detected ppb-levels and was thus potentially suitable for asthma monitoring. However, although the sensor included a small microporous working electrode chip, it had off-chip reference and counter electrodes together with an external liquid electrolyte supply that needed continuous refilling, resulting in a large size and a non-integrated cumbersome manufacturing.

In the present work, a highly integrated, 10 × 10 × 1 mm, ppb-level amperometric NO gas sensor chip with wafer-level fabricated electrodes and liquid electrolyte chamber is described for the first time. The sensor was designed and characterized for its sensitivity to NO gas and for its response time with respect to asthma monitoring application. In addition, the sensor was characterized for selectivity to electrochemically sensitive gases such as carbon monoxide (CO) and ammonia (NH₃) present in the exhaled breath which, potentially could interfere with electrochemical sensors. Typical concentrations of CO and NH₃ in exhaled breath are in the range of 0–8 ppm and 0–1 ppm, respectively. In order to maximize the sensor operation life time a special sensor sealing mechanism was utilized to minimize the electrolyte evaporation loss and hence to avoid refilling of the electrolyte.

2. Sensor design

To obtain the required ppb-level sensitivity a high surface area of the working electrode is essential. Here, this is realized through a microporous working electrode with a nanostructured Nafion™ coating. The integration of a liquid electrolyte volume together with the three sensor electrodes provide for constant moistening of the working electrode thus making the sensor less sensitive to changes in ambient humidity. Figure 1 shows a schematic illustration of the sensor design, the amperometric voltage biasing and the current measurement arrangement of the three electrodes.

3. Fabrication process of the sensor

This section describes the fabrication process and the assembly of the integrated gas sensor. This includes the wafer level fabrication of the microporous working electrode using a silicon on insulator (SOI) wafer and its integration with a glass wafer containing the counter and the reference electrodes. Each sensor has an electrolyte chamber, formed by an etched cavity between the SOI wafer and the glass wafer and used for storing the electrolyte. The electrolyte used in the sensor was 5%wt H₂SO₄ liquid solution together with a Nafion layer covering the microporous grid structure. A combination of Nafion electrolyte and water was reported earlier.

3.1 Working electrode and electrolyte chamber fabrication

The microporous grid structure of the working electrode was fabricated using an SOI wafer with a 250 μm thick device layer fusion bonded to a 500 μm thick handle wafer having
To begin with, the SOI wafer was oxidized with a 3 μm thick SiO₂ layer in an oxidation furnace. The oxidized device layer of the SOI wafer was patterned using photolithography to form a triangular arrangement with a 20 μm beam width and 120 μm distance between the beams, as illustrated in the inset of figure 1(b). The oxide layer was then etched using reactive ion etching (RIE) (Applied Materials Precision 5000 Mark II, USA) for approximately 25 min to expose the device layer. The device layer was etched through using an ICP Deep RIE etcher (Surface Technology Systems, UK) for 100 min to form the microporous grid structure (figure 2(a)). To protect the side walls of the microporous grid during subsequent processing, the SOI wafer was oxidized with a 3 μm thick SiO₂ layer.

A 300 μm thick Borofloat™ glass wafer was used as a substrate to fabricate the counter and the reference electrodes of the sensor in a process flow illustrated in figure 4. To begin with, through glass vias (TGVs), 150 μm in diameter, were drilled through the substrate to enable electrical contacts for the reference and the counter electrodes (figure 4(a)). 500 nm silver was evaporated around and into the via holes using a shadow mask defining the electrode contact areas. The wafer was angled at approximately 45° to the line of deposition to ensure deposition of silver on the side walls of the TGVs (figure 4(b)). Silver counter and reference electrodes were deposited on the opposite side of the wafer using the same deposition process but another shadow mask (figure 4(c)). A close up view of the counter and the reference electrodes containing the TGVs is shown in figure 5. To prepare the reference electrodes for the amperometric measurements the silver layer surface on the reference electrodes was transformed into silver oxide by dipping the wafer in a 5%wt H₂SO₄ solution with a voltage of 1.0 V applied between a platinum cathode and the interconnected reference electrodes for two minutes, as illustrated in figure 4(d). A change in the color from silver to white was observed during the passivation of the reference electrode.

3.3. Sensor assembly

To form an integrated sensor, the glass wafer containing the counter and reference electrodes and the SOI wafer containing working electrodes were assembled by anodic bonding. Individual sensors were then obtained by dicing the bonded wafer.
wafer stack. Figure 6 shows a schematic representation of a single sensor after the final assembly. Figure 7(a) shows a photograph of the gas sensor chip after dicing. The chip size is 10 mm × 10 mm and approximately 1 mm thick. The SEM image in figure 7(b) shows the cross section of a sensor with the electrolyte chamber integrated in the chip.

In order to achieve the high ppb-level sensitivity, the surface area of the working electrode area was dramatically increased by the formation of a highly nanoporous layer of Nafion. This was done by immersing the integrated sensor chip into a beaker containing 5%wt Nafion solution (Sigma Aldrich, USA) which was then transferred to a vacuum desiccator (Model 550, Kartell, Italy) and pumped to approximately 0.2 bar (abs.). The low pressure in the vacuum chamber desiccator helps in removing air bubbles that could be trapped within the sensor cavity. The sensor was allowed in the desiccator for 5 min, after which the vacuum pump was turned off and the pressure was slowly increased to atmospheric
pressure by opening a valve connected to the chamber. The sensor chip was removed from the desiccator and dried using filter paper (Whatman 903® DBS paper, Whatman plc, UK) which, rapidly absorbed excess Nafion solution contained in the electrolyte chamber. The chip was then allowed to dry in air for 30 min after which the TGVs were sealed with a silicone sealant (Silicone sealant 7091, Dow corning, USA).

4. Evaluation procedure

To characterize the sensor, gold bond wires were connected to the contacts of the three electrodes using a silver conductive adhesive (Electrolube, UK). In order to fill the electrolyte chamber with electrolyte without trapping air bubbles, the sensor chip was immersed in a beaker containing the electrolyte solution and subjected to a desiccator vacuum treatment to ensure complete and gas bubble free filling of the electrolyte chamber. The electrolyte-filled chip was then mounted in a custom-made chip holder that holds the sensor chip together with an active carbon fiber filter taken out from a commercial NO sensor (03-2030, Aerocrine AB, Sweden). The role of the filter is to reduce interference from other gases contained in the breath.

4.1. Measurement set-up

Figure 8 shows an illustration of the mechanical sealing module that was used for characterizing the integrated sensor. The module consists of a sensor housing (top part and bottom part) together with a plunger that is used for sealing the sensor. In order to prevent the evaporation of the electrolyte, the sealing of the sensor was ensured by a compliant layer consisting of a soft sealing adhesive tape (Double sided acrylic adhesive, Specialist tapes, UK) that was attached to the head of the plunger. For gas concentration measurements, the plunger was manually pulled upwards to allow the gas to reach the sensor.

To test the sensor for different gases and gas concentrations a measurement set-up was arranged as illustrated in figure 9. In this arrangement a 200 ppb NO in N₂ calibration gas (AGA gas AB, Sweden) and residues of NOₓ from the N₂ gas were removed using a scrubber (Dräger, type 1140, Germany). To measure the selectivity of the sensor to interfering gases, the NO gas was switched to 45 ppm CO in N₂ using a two-way valve. In order to measure the selectivity to NH₃ gas, the CO gas bottle was exchanged with a 45 ppm NH₃ in N₂ (AGA gas AB, Sweden) gas bottle. In order to humidify the gas mixture, a custom-made in-line humidifier consisting of a cylinder containing moistened tissue paper (TX609, Texwipe, USA) was used. To keep the humidity constant, small volumes of water was manually injected into the cylinder using a needle and syringe (figure 9) when the measured humidity deviated from the desired operating humidity.

To measure the working electrode current, the sensor was connected to a potentiostat (DY2011, Digi-ivy, USA). Two mass flow controllers (F201CV, Bronkhorst EL-flow, Netherlands) and two flow sensors (AWM5102, Honeywell, USA) were used to control and measure the flow rate, respectively. To measure the operating humidity of the sensor, a humidity sensor (HIH 4000, Honeywell, USA) was placed inside the sensor housing (bottom part) of the mechanical sealing module. A LabVIEW™ program was used to access the data from the humidity sensor and the flow sensors. The humidity around the sensor was held constant to approximately 50% RH for all measurements. The gas flow rate was maintained constant at 550 ml min⁻¹ for all measurements. All the measurements from the sensor were carried out with the working electrode biased at +0.95 V as compared to the reference electrode.

4.2. Measurement methods

The working electrode current from the sensor has a slow drift over a period of time. To compensate for this drift, the background current, i.e. the current at zero NO concentration, was measured directly prior to each gas concentration measurement. This was done by measuring the background current in a pure nitrogen flow, then switching to the NO gas concentration to be measured and taking a measurement of the working electrode current at that concentration. After recording the
working electrode current, the NO gas flow was stopped and the N₂ gas flow was started. A pulsed method of switching back and forth between the NO and N₂ gas was used. The output current of the sensor for a given NO gas concentration was then calculated as the difference between the working electrode current and the background current. To determine the sensitivity of the sensor, the output current was measured by sweeping the NO concentration and taking measurements at 25 ppb, 50 ppb, 110 ppb and 200 ppb, respectively. Four such sweeps were carried out leading to four values of the output current at each concentration which were then averaged. The selectivity of the sensor was estimated by measuring the CO sensitivity by adding CO concentrations from 10 ppm to 32 ppm. For comparison, the selectivity was also tested at another bias voltage, \(V_{\text{bias}} = 0.7\) V used earlier [16]. To measure the response time of the sensor, the gases were alternately switched between 200 ppb NO and pure N₂. The response time, \(t_{90}\) of the sensor was estimated when the output current was observed to reach an average maximum value of \(I_{\text{Omax}}\) for 200 ppb concentration.
In order to assess the evaporation time of the electrolyte, two types of experiments were performed. In the first experiment, the output current and the volume of the electrolyte were measured when the plunger of the mechanical sealing module was kept open. A flow of 550 ml min\(^{-1}\) of N\(_2\) was maintained and the humidity was kept constant at 50% RH. Gas with 200 ppb NO concentration was administered at regular intervals to the sensor and the output current was measured. In the second type of experiment, the liquid volume loss was measured by weighing a liquid filled sensor chip using an external precision scale. Both for a sensor with constantly open plunger (at 550 ml min\(^{-1}\) N\(_2\) flow and 50% RH humidity) as well as for a sensor with a constantly closed plunger sealing mechanism.

### 5. Results and discussion

The fabricated wafer contained 44 sensors of which 15 sensors were tested for NO gas and found functional. Remaining sensors were tested for reliability issues such as handling, electrolyte evaporation, Nafion coating, and packaging. The sensor was characterized for its sensitivity to NO gas, response time, and selectivity to CO and NH\(_3\) gases. The evaporation of the electrolyte in the sensor was characterized for both open and closed sealing mechanism.

#### 5.1. NO sensitivity

The average value of the output currents for four different concentrations between 0 and 200 ppb is plotted in figure 10. The output current, \(I_0\) was found to be linear with the NO gas concentration. Based on a linear fit, a sensitivity of 0.04 nA ppb\(^{-1}\) was calculated, which is in agreement with our earlier fabricated non-integrated sensor [16]. The sensor detects NO gas in the lower limit of 25 ppb and is thus within the limit for detecting asthma. The sensitivity of the sensor can likely be further improved by increasing the pore surface area of the working electrode, i.e. by a denser grid pattern.

#### 5.2. Selectivity to CO and NH\(_3\)

The selectivity of the sensor to interfering gases in the exhaled breath such as CO and NH\(_3\) were determined by calculating...
the ratio of the respective sensitivities to NO gas sensitivity. The CO gas sensitivity was measured for two different bias voltages and plotted in figure 11. With $V_{\text{bias}} = 0.7 \, \text{V}$, the sensitivity was calculated using the linear fit and found to be approximately $1.4 \, \text{nA} \, \text{ppm}^{-1}$ and with a $V_{\text{bias}} = 0.95 \, \text{V}$, the sensitivity was calculated to be $0.036 \, \text{nA} \, \text{ppm}^{-1}$. Thus, the selectivity of the sensor to CO is approximately 1000 for the higher bias voltage. In exhaled breath, CO gas concentration can be between 500 to 1000 times higher than the NO concentration, indicating that the sensor has a selectivity to CO within the range to be applicable in asthma monitoring [19]. The reduction of CO sensitivity with increasing bias could be due to the oxidation of the platinum at the working electrode [18, 22, 23]. Since the sensor is exposed to ambient atmosphere and real breath samples contain oxygen, processes like this may affect selectivity. For NH$_3$, the output current was found to be below the detection limit and hence was not measurable when the sensor was tested with 45 ppm NH$_3$ gas.

5.3. Response time

The response time of the sensor was determined by estimating the rise time ($t_{90}$) of the sensor, i.e. the time it takes to reach 90% of the maximum output current, $I_{O_{\text{max}}}$ which was calculated by using the estimated average maximum value of the measured output current. This resulted in a response time of 12 s, as shown in figure 12(a). This is considerably faster than the response times of commercially available ppb-level NO sensors. In exhaled breath, the NO concentration profile reaches a stable value after 7 s and a suitable measurement interval of the exhalation phase is suggested to be between 7–10 s [6]. This means that the present design has a response time performance which likely is within optimization reach for use in real time asthma detection applications. Figure 12(b) shows a background current drift of approximately 0.86 nA min$^{-1}$, which corresponds to 20 ppb min$^{-1}$ in terms of NO concentration drift. This means that for the 12 s of the measurement time of the response, the drift component of the signal amounts to about 4 ppb. This is an acceptable level of drift for asthma monitoring applications, where the NO concentrations typically are around 50 ppb.

5.4. Operation lifetime

The electrolyte in the electrolyte chamber will evaporate through the microporous working electrode. In order to have the electrolyte liquid last longer a special sealing mechanism was incorporated in the mechanical sealing module. The electrolyte evaporation was assessed with two types of experiments. In the first experiment, the evaporation of the electrolyte and its effect on the output current was measured when the plunger of the mechanical sealing module was kept open. In order to determine the working duration time of the sensor under plunger open condition, the output current, $I_O$ was measured for 200 ppb NO concentration at five different intervals. The output current was measured to be approximately 7 nA for the first four measurements during 80 min, but then dropped to zero after 94 min as shown in figure 13. In a second type of experiment the liquid volume loss over time of a liquid filled sensor chip with an open plunger was investigated. The liquid volume loss was determined by weighing the sensor chip at eight different occasions. The measurements plotted in figure 14 show that the electrolyte chamber has been emptied through evaporation after 100 min. This is in good agreement with the measurements shown in figure 13 where the sensor stopped to work after 94 min, presumably due to a dried out electrolyte chamber. Hence, the sensor seems to be functional even if the electrolyte has partially evaporated. A reason for this could be the hygroscopic property of the Nafion layer covering the interior of the sensor. This may help
keeping the electrodes moist even if the electrolyte has partially evaporated. It should be noted however, that the sensor signal was only measured at 200 ppb NO and any changes in linearity as a result of evaporation was not studied.

Using the same weighing procedure as above, the electrolyte volume loss was also measured when the plunger of the mechanical sealing module was kept closed. Figure 15 shows that the sensor lost about 1/3 of the liquid volume in three weeks, indicating after extrapolation that the sensor would still contain liquid after nine weeks. Since the measurements of figures 13 and 14 clearly indicate that the sensor will work as long as there is any electrolyte liquid still left in the sensor it can be functional for NO measurements for nine weeks with this experimental sealing module set-up. The decrease in the volume of the electrolyte in the closed mode is likely caused by small leaks between the sealing plunger and the sensor chip and can most likely be further reduced by optimizing the sealing material and mechanism.

The measurements illustrated in figures 14 and 15 shows that the liquid loss rate is 0.3 μl min⁻¹ in the open measurement mode and 0.5 μl d⁻¹ in the closed mode. Assuming a needed open period of 30 s (allowing both zero-level and sample measurements), an electrolyte liquid loss of approximately 0.15 μl/measurement can be calculated. This means, for example, that the current design would enable approximately 200 measurements. This is a fully sufficient operation lifetime of a NO sensor in asthma monitoring applications.

The sealing of the sensor using the mechanical sealing module was demonstrated to be an effective solution comparable to multiple Teflon layers used in the commercial sensors. Using this method, evaporation of the electrolyte was minimized without sacrificing the response time. It is conceivable that the mechanical sealing module can be reduced in size and an electrically controlled actuator mechanism for the opening and closing of the sealing mechanism can be included for the asthma monitoring application.

6. Conclusions

A highly integrated, 10 × 10 × 1 mm, ppb-level detection amperometric NO gas sensor chip with wafer-level fabricated electrodes and liquid electrolyte chamber is described for the first time. Using a mechanical sealing module the electrolyte evaporation was minimized resulting in a potential for about 200 measurements. The sensor, which was designed to be applicable for use in real-time measurement of NO gas in handheld asthma detection applications, showed a measured sensitivity of 0.04 nA ppb⁻¹ and a response time of 12 s. A high selectivity to breathing gases such as carbon monoxide (CO) and ammonia (NH₃) precludes any interference with the NO concentration measurement. Future work would focus on
investigations using breath samples from healthy and asthmatic patients.

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